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Predicting soil organic carbon sequestration in the southeastern United States with EPIC and the soil conditioning index

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Abstract: The Soil Conditioning Index (SCI) is a relatively simple model that predicts the consequences of cropping systems and tillage practices on the status of soil organic matter in a field. The SCI is administered by the USDA Natural Resources Conservation Service to predict a positive or negative trend in soil organic matter based on knowledge of field operations, erosion loss, and organic matter inputs but has not been adequately tested against long-term management conditions that could affect soil organic carbon (SOC) dynamics. We calibrated the Environmental Policy Integrated Climate model (EPIC v. 3060) for three major land resource areas in the southeastern United States using 5 to 10 years of measured SOC data to develop a predictive relationship of SOC for 50-year simulations with SCI values. Management systems included conventional tillage and no tillage in (1) a two-year rotation of wheat (*Triticum aestivum* L.)/sorghum (*Sorghum bicolor* [L.] Moench)–corn (*Zea mays* L.) with low and high fertilizer application on a Blackland Prairie site in Texas, (2) a two-year rotation of corn–cotton (*Gossypium hirsutum* L.) with and without dairy manure application on a Coastal Plain site in Alabama, and (3) in monoculture cotton on a Mississippi Upland site. Across sites and fertilizer conditions, SOC sequestration during 50 years of using EPIC was greater under no tillage (9.5 Mg ha^{-1} [4.2 tn ac^{-1}]) than under conventional tillage (6.3 Mg ha^{-1} [2.8 tn ac^{-1}]) ($p < 0.01$). Although simulated SOC using EPIC was weakly related to SCI values, the relationship fit well within a larger dataset from the southeastern United States. The comprehensive EPIC model and the simpler SCI model could be useful tools to determine SOC storage among different management systems in the southeastern United States.

Key words: carbon sequestration—conservation tillage—modeling—soil organic carbon

Soil organic C (SOC) has important implications for global climate change since it can serve as both a source and a sink for atmospheric CO_2. Until the 1950s, a greater quantity of CO_2 was emitted into the atmosphere from land use change and soil cultivation than from fossil fuel, but now burning of fossil fuels is more dominant (Lal 2003).

A decline in SOC can be simply described from an altered balance between C inputs and C outputs. Reduced input of organic matter has been historically the result of deforestation, biomass burning, and conversion of natural systems to agriculture. Enhanced decomposition of soil organic matter increases CO_2 emission, primarily as a result of tillage practices which enhance soil microbial activity by releasing protected SOC within stable aggregates (Post and Kwon 2000; Lal 2003). Many studies have shown the benefit of conservation tillage, winter cover cropping, crop rotation, and residue management for storing SOC (Hunt et al. 1996; Sainju et al. 2002; Terra et al. 2005). However, there are only a few studies that have measured long-term impacts (>10 years) of tillage and residue management on SOC (Dick et al. 1998; Hendrix et al. 1998; Wright and Hons 2005). Regional differences in SOC sequestration can be strong and related to climate, soil, and management conditions (Franzluebbers and Follett 2005). Franzluebbers (2005) reviewed the literature pertinent to SOC sequestration and greenhouse gas emissions from agricultural activities in the southeastern United States and found that most studies were >5 years in duration, but <20 years. Long-term studies are needed to adequately characterize SOC under different tillage and residue management systems and to determine, for example, whether SOC is actually increasing with time under conservation tillage or just decreasing more slowly than under conventional tillage.

Simulation models are a practical way to understand how a system works and provide an inexpensive and expedient alternative to long-term field studies, although obviously providing only a simulation of reality (Abrahamson et al. 2005; 2006). The Environmental Policy Integrated Climate (EPIC) model (Williams et al. 1984) now includes a C- and N-transformation submodel (EPIC v. 3060) with concepts and equations derived from the CENTURY model (Izaurralde et al. 2001; 2006). Simulations of crop yield, soil erosion, water quality, and SOC with EPIC v. 3060 have been validated against data from various studies around the world (Chung et al. 1999; Izaurralde et al. 2001, 2006; Potter et al. 2004; Feng et al. 2005). Recent studies have calibrated EPIC v. 3060 against field data by optimizing sensitive parameters to improve model performance but have found overpredictions of SOC for soils low in SOC and underpredictions of SOC for soils high in SOC (Izaurralde et al. 2001, 2006; Potter et al. 2004; Causarano et al. 2007).

Initialization of EPIC may not be necessary in many cases for simulating SOC because the model equilibrates dynamically in the first few years when soil and climatic processes respond to management practices. However, comprehensive models such as EPIC that include dozens of parameters are constantly being updated and improved based on new findings from different simulation studies where measured data are available.

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Adjustment of sensitive model parameters allows more accurate simulation of key processes and predictions and can minimize inherent model errors, especially when the model is applied to different soil, crop, and climate conditions than those under which it was originally developed (Abrahamson et al. 2005).

The Soil Conditioning Index (SCI) model has been incorporated as part of the Revised Universal Soil Loss Equation (RUSLE2), a prediction tool containing both empirical and process-based relationships to predict soil erosion from rainfall and runoff (USDA NRCS 2006). A SCI value is derived from the RUSLE2 model based on various agricultural management inputs and conditions. The SCI is a function of three components known to affect SOC: (1) organic material grown on or added to soil, (2) field operations that alter organic material placement in the soil profile and that stimulate organic matter breakdown, and (3) erosion that removes and sorts surface soil organic matter (USDA NRCS 2003). The USDA Natural Resources Conservation Service (NRCS) has used the SCI to predict changes in SOC based on different agricultural management practices and to calculate conservation payments to landowners enrolled in the Conservation Security Program (Hubbs et al. 2002). Payments to landowners have been based on a linear increase with SCI up to a maximum value. For example, current payments have been calculated as \$28.65 ha^{-1} y^{-1} (\$11.60 ac^{-1} yr^{-1}) times a positive SCI value.

In a recent study, we simulated SOC during 50 years with the uncalibrated EPIC v. 3060 model in three Major Land Resource Areas (MLRAs) in the southeastern United States and found that simulated SOC sequestration was greater with NT than with conventional tillage (CT) and with more diverse crop rotation systems than with continuous cotton (*Gossypium hirsutum* L.) under no tillage (NT) (Abrahamson et al. 2007). Discrepancies in measured and simulated cotton yield relative to tillage treatment led us to the hypothesis that calibration of certain key parameters might improve yield simulations and biomass production, important variables for accurate simulations of SOC. Our objectives were to (1) calibrate key sensitive parameters of EPIC v. 3060 using measured SOC data from three studies in the southeastern United States, (2) simulate SOC storage and accumulation rates during 50 years of CT and NT management using EPIC v. 3060, (3) develop a relationship between SCI and predicted SOC from EPIC v. 3060, and (4) evaluate the adjusted parameter values in EPIC v. 3060 for use across locations and management systems. Our long-term objective is to develop reasonably efficient and accurate predictions of SOC storage and accumulation rates among different conservation management systems throughout the warm, humid region of the southeastern United States. Until more long-term studies of the effects of agricultural management systems on SOC become available in the southeastern United States, simulation models such as EPIC can provide a valuable tool to evaluate the impact of alternative agricultural management practices on SOC processes, storage and accumulation rates in conjunction with validation using short-term measurements of SOC. In addition, being able to relate the SCI to a rate and quantity of SOC accumulation over several decades would be valuable information in deliberations for future global C management and trading.

Materials and Methods

Site Descriptions. Study sites were located in the Texas Blackland Prairie (MLRA 86) in eastern Texas, the Southern Coastal Plain (MLRA 133) in central Alabama, and the Southern Mississippi Valley Silty Uplands (MLRA 134) in northern Mississippi. These sites represented (1) different soil textures, i.e. clay, sandy loam, and silt loam, respectively, (2) availability of 10, 5, and 8 years of measured SOC data, respectively, and (3) crop production and management systems common in the southeastern United States.

Measured SOC data for the Blackland Prairie site were obtained near Temple, Texas (31° 5' N, 97° 35' W, elevation 210 m [700 ft]) from a study reported in Potter et al. (1998). Mean annual precipitation was 860 mm (33.9 in), and mean annual temperature was 19°C (66°F). Field management was conducted for 10 years on a Houston Black clay (fine, montmorillonitic, thermic Udic Pellustert) that had previously been under CT for an extended period and had developed a stable SOC level (Mann 1986; Potter et al. 1998). Management treatments included a two-year rotation of winter wheat (*Triticum aestivum*)/grain sorghum (*Sorghum bicolor* [L.] Moench)–corn (*Zea mays* L.) under CT and NT with low and high fertilizer rates in a split plot design. The low fertilizer rate was applied as 28 kg N ha^{-1} (25 lb ac^{-1}) and 12 kg P ha^{-1} (11 lb ac^{-1}) in each crop. The high fertilizer rate was applied as 112, 140, and 168 kg N ha^{-1} (100, 125, and 150 lb ac^{-1}) and 27, 32, and 37 kg P ha^{-1} (24, 29, and 33 lb ac^{-1}) to wheat, sorghum, and corn, respectively. We calibrated EPIC v. 3060 against measured SOC in the surface 20 cm (8 in) of soil, where management effects were significant (Potter et al. 1998).

Measured SOC data for the Coastal Plain site were obtained from a study reported in Causarano et al. (2007) near Shorter, Alabama (32° 4' N, 85° 9' W, elevation 68 m [227 ft]). Annual precipitation averaged 1,356 mm (53.5 in), mean monthly low and high temperatures were 12°C and 24°C (54°F and 75°F), and the growing season was 240 days. The soil was a Marvyn sandy loam (fine-loamy, kaolinitic, thermic Typic Kanhapludults) on a site with a long history of CT row cropping. Four management systems were simulated in a two-year rotation of corn–cotton with and without dairy manure under CT and NT. The NT system included winter cover crops, but the CT cropping system did not. Measured SOC data at the end of five years from the summit landscape position at 0 to 30 cm (0 to 12 in) depth were used to calibrate EPIC v. 3060. The summit landscape position was selected because it represented a typical, level farmland (0% to 2% slope) characteristic of the southeastern region.

Measured SOC data for the Mississippi Upland site were obtained near Senatobia, Mississippi (34° 31' N, 89° 57' W, elevation 59 m [197 ft]) reported in Rhoton (2000). Annual precipitation was 1,340 mm (52.8 in), and annual average daily minimum and maximum temperature was 10.6°C and 23.9°C (51°F and 75°F), respectively. The site had recently been in pasture prior to cotton cropping. Management systems consisted of CT and NT in continuous cotton with a winter wheat cover crop on a Grenada silt loam (fine-silty, mixed, active, thermic Oxyaquic Fraglossudalf). Cotton received a broadcast application of 13-13-13 (N-P_2O_5-K_2O at 50 kg ha^{-1} [45 lb ac^{-1}]) based on soil test data and was side-dressed with 50 kg N ha^{-1} (45 lb ac^{-1}) of ammonium nitrate each year. Fertilizer was incorporated with CT and left on the surface with NT (Rhoton 2000). Measured SOC data in the surface 15.2 cm (6 in) were used to calibrate EPIC v. 3060 for an eight-year period.

Soil properties at the Blackland Prairie site were obtained from the USDA NRCS SSURGO and STATSGO databases (Soil Survey Staff USDA NRCS 2007; Soil Survey Staff USDA NRCS 2007) included with EPIC v. 3060. For the other sites, measured soil properties were used (table 1). Climatic inputs were generated using WXGEN in EPIC (Williams and Sharpley 1990), based on long-term conditions at weather stations near the three locations (US DOC NOAA NESDIS NCDC 2007). Management operations for each site were based on those reported in the field studies.

Parameter Adjustments in Environmental Policy Integrated Climate. Causarano et al. (2007) selected crop and soil parameters in EPIC v. 3060 for the Alabama Coastal Plain site based on a sensitivity study (Wang et al. 2005) using an optimization procedure to determine variation in output relative to parameter variation. Causarano et al. (2007) compared predicted and measured values for crop yields and soil C components with uncertainty analysis and aggregated likelihood functions to select parameter values for (1) the biomass/energy ratio, (2) harvest index (HI), (3) fraction of humus in the passive soil C pool (FHP), (4) microbial decay coefficient (PARM20), and (5) microbial activity in the top soil layer (PARM51). For our study, we optimized parameters by iteration within the range of default values suggested in the EPIC model for HI (cotton) and PARM51 and within the range of values found by Wang et al. (2005) or Rosenthal and Gerik (1991) for biomass/energy ratio, HI (corn), FHP, and PARM20 to achieve best agreement with measured SOC under CT management at each location.

Because the FHP and PARM20 parameters explained most of the variance in SOC during the sensitivity analysis of EPIC v. 3060 at the Alabama Coastal Plain site (Causarano et al. 2007), we initialized the values for these two parameters in the model based on measured data from the site. The value for the FHP parameter (0.70) was based on measurement of particulate organic C (Causarano et al. 2007). The value of FHP was set to 0.80 for the Blackland Prairie site, since Potter et al. (2004) achieved good results using this value in the EPIC model at pasture and grassland sites near Temple, Texas. For the Mississippi Upland site, we used an estimate of 0.35 for FHP based on simulations of passive SOC by Liu et al. (2003) using the CENTURY model (Parton et al. 1987, 1993) and the Erosion-Deposition-Carbon Model (Liu et al. 2003) for the same soil and area in Tate County, Mississippi.

After optimizing the FHP parameter for CT management at each location, we adjusted the microbial decay coefficient (PARM20), if needed, to bring simulated SOC within the range of the standard error of measured values, or within 10% of measured values (simulated minus measured and then divided by measured) if standard errors of measurements were not available. If more accuracy was needed, we adjusted the microbial activity coefficient (PARM51) in the top-soil layer within the range of suggested values in the model.

The fraction of microbial biomass (FBM) was not found to be sensitive by Wang et al. (2005), but since Causarano et al. (2007) presented data to estimate FBM, we used the same value of 0.04 used in their study for the Coastal Plain simulations and as a starting FBM value for the Blackland Prairie simulations. For the Mississippi Upland simulations, we used a FBM value of 0.15, based on simulations of the fast SOC pool by Liu et al. (2003) for the same study area and soil. The fast pool of SOC should include microbial biomass C and possibly an additional mineralizable C fraction but would depend upon a model's representation of SOC dynamics. The soil organic matter submodel in EPIC v. 3060 follows the same approach used in the CENTURY model where SOC is split into active, slow, and passive humus pools (Izaurralde et al. 2006).

While adjusting parameters to predict SOC, we also checked predicted yields and adjusted the biomass/energy ratio and the harvest index (HI) parameters within the range of suggested values for corn and cotton to obtain an average yield that closely matched the average measured yield at or

Table 1

Selected initial soil properties used for EPIC v. 3060 simulations.

Depth from surface (m)	Bulk density ($Mg\ m^{-3}$)	Sand ($g\ kg^{-1}$)	Silt ($g\ kg^{-1}$)	Soil pH	Organic C ($g\ kg^{-1}$)
Blackland Prairie (Houston black clay)					
0.01	1.05	48	390	8.0	15.0
0.18	1.35	48	390	8.0	15.0
0.48	1.20	54	393	8.3	12.8
0.71	1.25	49	371	8.2	10.9
0.91	1.30	38	368	8.0	8.4
1.12	1.26	60	351	8.0	8.7
1.35	1.30	64	382	8.1	4.7
1.51	1.36	57	402	8.3	3.8
2.00	1.32	66	419	8.2	2.8
Coastal Plain (Marvyn sandy loam)					
0.05	1.59	584	200	6.0	7.0
0.20	1.65	545	268	6.0	5.3
0.30	1.55	537	246	5.3	5.3
0.46	1.36	450	216	5.3	3.3
1.04	1.36	420	200	5.3	2.8
1.42	1.37	452	162	5.3	2.6
Mississippi Uplands (Grenada silt loam)					
0.01	1.45	19	812	6.0	11.0
0.08	1.45	16	788	6.0	10.4
0.17	1.45	19	735	5.7	5.0
0.27	1.45	26	803	5.5	2.7
0.36	1.28	31	803	5.4	2.2
0.45	1.44	31	803	5.4	2.2
0.55	1.51	31	803	5.6	1.8
0.64	1.51	10	717	5.7	1.1
0.74	1.54	74	476	5.6	0.9
0.89	1.58	NA	NA	5.6	0.9

Note: NA = not available.

near the three sites (Torbert et al. 2001; USDA NASS 2007; Causarano et al. 2007).

EPIC-Simulated Output Analyses. After adjusting parameters and simulating SOC for each measured depth in each management system and MLRA, we regressed simulated SOC on year in each MLRA and management system to obtain an annual rate of change with time. Annual SOC estimates within a MLRA and management system were also fitted to a non-linear exponential model, a process-based fit, to obtain total SOC sequestered during 50 years:

$$Y_t = A + B \times (1 - \exp^{-k \times t}), \tag{1}$$

where, Y is SOC sequestered (Mg ha^{-1}) at time t (y), A is initial SOC (Mg ha^{-1}), B is potential SOC sequestration (Mg ha^{-1}), and k is the non-linear rate of SOC sequestration (y^{-1}). Simulated annual SOC estimates and the nonlinear fit of estimates were plotted for each location and management system. The resultant single estimates for SOC and the linear slope for each MLRA and management system were used as independent estimates in an analysis of variance that used MLRA and fertilizer combinations (MLRA 86 low fertilizer, MLRA 86 high fertilizer, MLRA 133 without manure, MLRA 133 with manure, and MLRA 134) as a blocking variable ($n = 5$) and tillage (conventional and no tillage) as a response variable ($n = 2$). Significance between tillage means with true replications was declared at $p = 0.05$.

Soil Conditioning Index. Using the same management conditions and locations as for the EPIC v. 3060 simulations, we calculated Soil Conditioning Index (SCI) values for a 50-year period for each management system and MLRA using RUSLE2 (USDA NRCS 2006). The RUSLE2 model was used with databases from the RUSLE2 website (USDA 2007), which contain location- or state-specific climate data, specific soils data for a county or soil survey area, and specific sets of crop management templates for a crop management zone or area of the country. Users may also build their own crop management templates and adjust other inputs such as slope, residue, topography, surface cover type, and other variables. The same climate data files and soil series that were used for our EPIC v. 3060 model simulations were selected, and the crop and field management/operations templates were built to duplicate those used for EPIC. Total EPIC-simulated SOC sequestration during 50 years and annualized SOC accumulation rates were tested for their relationship against SCI values from RUSLE2 using linear regression ($n = 10$).

Cross-Location Comparison of Environmental Policy Integrated Climate Parameters. Finally, we compared the simulated annual SOC accumulation rate using the optimized parameter set for one location at each of the other two sites to evaluate the applicability of one parameter set across MLRAs. Linear slopes among sites and parameter sets were considered different if 95% confidence intervals did not overlap. Conceptually, being able to use a universal set of parameters across MLRAs in the southeastern United States would be efficient and would contribute to a more robust modeling approach. However, differences in SOC estimates with different parameter sets could also help determine model biases or errors within the region. General linear models were analyzed using PROC GLM (SAS Institute 2003) and nonlinear models were analyzed using Sigma Plot for Windows v. 8.02.

Table 2

Value of selected carbon cycle parameters used to calibrate the EPIC model for the three sites in the southeastern United States.

	Passive humus fraction (FHP)	Microbial decay coefficient (PARM20)	Microbial activity in the top layer (PARM51)	Fraction microbial biomass (FBM)
Suggested range	0.3 to 0.9*	0.05 to 1.5*	0.1 to 1.0†	0.03 to 0.05†
Initial value	0.70	0.55	0.80	0.04
Value optimized during calibration for each site				
Blackland Prairie	0.80	0.55	0.80	0.04
Coastal Plain	0.70	0.57	0.80	0.04
Mississippi Upland	0.35	0.80	1.00	0.15

* Wang et al. (2005)

† EPIC suggested range

Results and Discussion

Environmental Policy Integrated Climate Calibration. At the Coastal Plain site, the microbial decay coefficient (PARM20) was increased from 0.55 to 0.57 to obtain simulated SOC within the standard error of measured values at the end of five years of conventional tillage (CT) management (table 2). The adjusted value for the fraction of humus in the passive pool (FHP) at the Blackland Prairie site (0.80) and for the Mississippi Upland site (0.35) resulted in simulated SOC within the established error of measured values (simulated minus measured and then divided by measured). The higher value of FHP for the Blackland Prairie site compared to the other two sites could be expected, since clay soils typically store greater SOC than sandy loam or silt loam soils as a result of stabilization with fine particles (Nichols 1984; Burke et al. 1989; Hassink 1994). Izaurralde et al. (2006) used a value of 0.75 in Canada, and Potter et al. (2004) also used a value of 0.80 for a soil in the Blackland Prairie. The value for FHP at the Mississippi Upland site seems low given the relatively fine texture of the soil. However, particle size in the Grenada silt loam is dominated by silt, which may exert uniquely unstable aggregate characteristics that could influence SOC turnover. Rhoton (2000) measured a pulse of SOC accumulation in the surface 2.5 cm (1 in) under no tillage (NT) during the first four years. In addition, a low value for FHP near the same study site was also simulated by the CENTURY model and Erosion-Deposition-Carbon Model (Liu et al. 2003).

Initial values of PARM20 and the level of microbial activity in the top layer (PARM51) did not need to be changed after adjusting the FHP parameter for the Blackland Prairie site (table 2). Simulated 10-year SOC values for the Blackland Prairie site were within 2% of measured values for all four management systems (table 3). For the Mississippi Upland site, PARM51 was increased from 0.80 to 1.0 to obtain 8-year simulated SOC values within 10% of measured SOC. A closer match of simulated SOC to measured SOC at the Mississippi Upland site could have been achieved with different PARM51 adjustments between CT and NT, but several iterations of different parameter values

Table 3
Simulated soil organic carbon (SOC) from the adjusted EPIC v. 3060 model and measured SOC at the end of each experimental period for each management condition at each site, as well as total and yearly rate of SOC accumulation during 50 years of simulation. Measured values were at the end of 10 years for the Texas Blackland Prairie site, at the end of 5 years for the Alabama Coastal Plain site, and at the end of 8 years for the Mississippi Upland site.

Management	Assumed initial SOC ($Mg\ ha^{-1}$)	Final measured SOC ($Mg\ ha^{-1}$)	Simulated SOC ($Mg\ ha^{-1}$)	Measured SE ($Mg\ ha^{-1}$)	(S–M)/M (%)	Simulated SOC change at 50 y ($Mg\ ha^{-1}$)	Rate of simulated SOC accumulation ($Mg\ ha^{-1}\ y^{-1}$)
Texas Blackland Prairie (0 to 20 cm depth)							
CT–low fertilizer	39.1	44.2	43.9	NA	−0.6	8.9	0.179
CT–high fertilizer	39.1	44.9	43.9	NA	−2.1	9.0	0.179
NT–low fertilizer	39.1	46.4	45.6	NA	−1.6	11.4	0.227
NT–high fertilizer	39.1	45.8	45.6	NA	−0.3	11.4	0.228
Alabama Coastal Plain (0 to 30 cm depth)							
CT–without manure	26.9	27.6	28.2	1.13	2.3	1.7	0.034
CT–with manure	26.9	33.9	34.0	0.65	0.4	12.3	0.246
NT–without manure	26.9	28.5	29.0	1.10	1.6	3.8	0.076
NT–with manure	26.9	36.6	36.3	1.26	−1.0	18.0	0.358
Mississippi Upland (0 to 15.2 cm depth)							
CT	18.0	16.3	17.7	NA	8.0	−0.25	−0.005
NT	18.0	20.0	18.2	NA	−9.0	2.9	0.058

Notes: M = measured. S = simulated. SE = standard error. CT = conventional tillage. NT = no tillage. NA = not available.

for this site showed that both CT and NT were very sensitive to slight adjustments in one or more of the parameters. We finally selected the best combination of parameters to minimize error between measured and simulated SOC and to avoid further adjustments that did not result in greatly improved agreement between measured and simulated SOC. It is possible that initial differences existed in the level of microbial activity (PARM51) between tillage treatments in the surface soil layer due to recent pasture land use and microclimatic differences at the soil surface under the two tillage treatments. Further assessments of EPIC v. 3060 against long-term data from field studies for these soils and this region of Mississippi are warranted to determine the accuracy of some of the parameter values optimized for this site for simulating SOC.

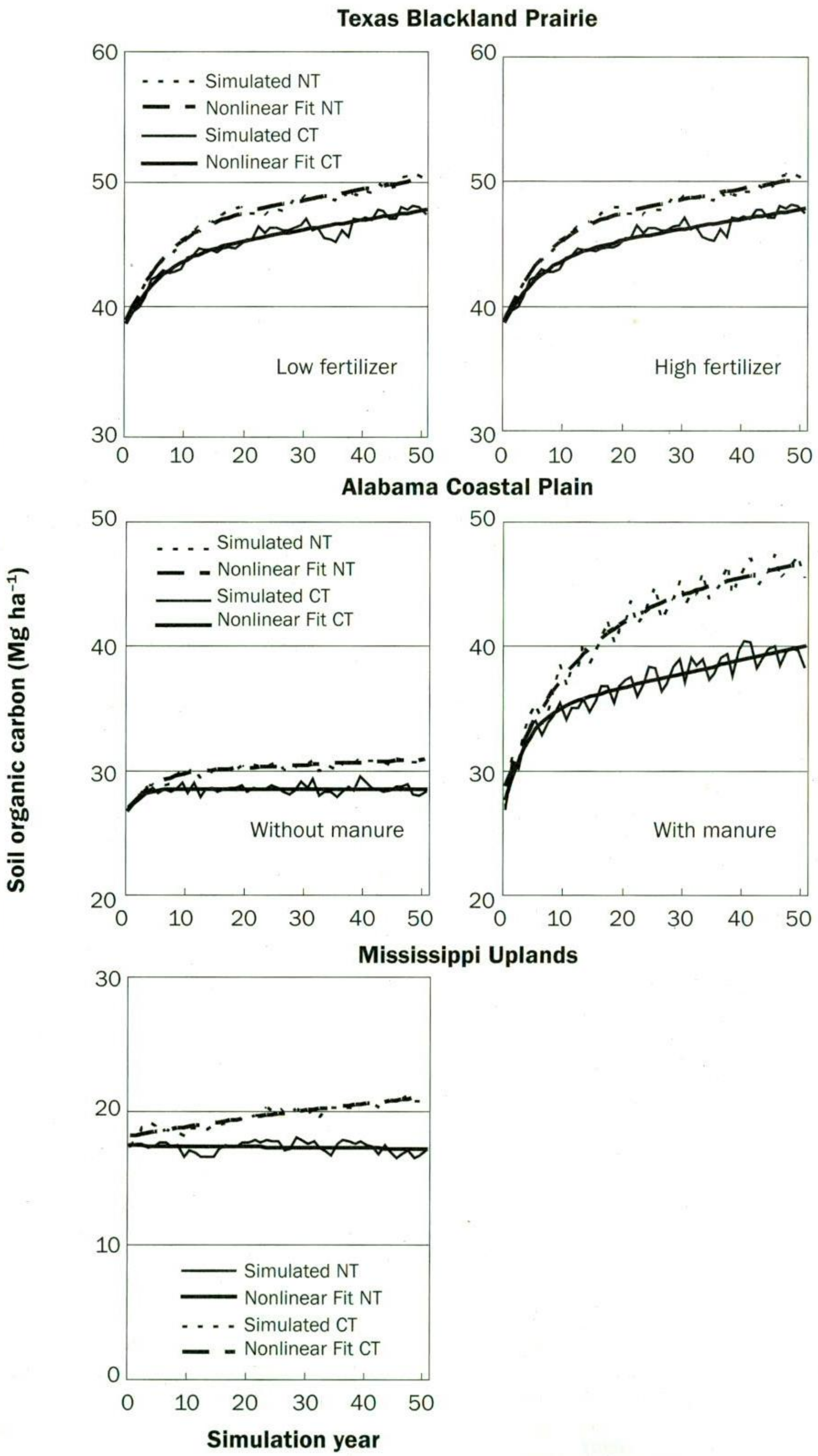
Environmental Policy Integrated Climate Simulation of Soil Organic Carbon and Crop Yields. Simulated 50-year SOC increased with time to varying degrees in all MLRAs and management systems, except under CT management at the Mississippi Upland site (figure 1). Simulated SOC values were within or only slightly outside the standard deviation of measured SOC values in both CT and NT during years 4 and 8 at the Mississippi Upland site (figure 2o). Measured SOC at the end of 8 years under CT at this location decreased by 1.9 $Mg\ ha^{-1}$ (0.8 $tn\ ac^{-1}$) in the 0 to 15.2 cm (6 in) depth, of which 89% occurred in the 0 to 2.5 cm (0 to 1 in) depth (Rhoton 2000). Total simulated SOC sequestration during 50 years averaged −0.3 $Mg\ ha^{-1}$ (−0.1 $tn\ ac^{-1}$) under CT and 2.9 $Mg\ ha^{-1}$ (1.3 $tn\ ac^{-1}$) under NT at the Mississippi Upland site, and the annual rate of change in SOC during 50 years of simulation was 0.03 ± 0.04 $Mg\ ha^{-1}\ y^{-1}$ (24 ± 40 $lb\ ac^{-1}\ yr^{-1}$) (table 3).

At the Blackland Prairie site, the difference between measured and simulated SOC at 10 years ranged from −2.1% in CT to −0.3% in NT (high fertilizer) (table 3 and figure 2a, 2d). Potter et al. (1998) calculated the rate of SOC sequestration under NT as the difference in SOC between NT and CT divided by the number of years of management, which was 0.09 $Mg\ ha^{-1}\ y^{-1}$ (80 $lb\ ac^{-1}\ yr^{-1}$) with high fertilizer and 0.22 $Mg\ ha^{-1}\ y^{-1}$ (196 $lb\ ac^{-1}\ yr^{-1}$) with low fertilizer. Total simulated SOC sequestered during 50 years averaged 8.9 $Mg\ ha^{-1}$ (4.0 $tn\ ac^{-1}$) under CT and 11.4 $Mg\ ha^{-1}$ (5.1 $tn\ ac^{-1}$) under NT at the Blackland Prairie site (table 3). Fertilizer inputs had no effect on simulated SOC at the end of 50 years, supported by the interpretation of measured data at the end of 10 years (Potter et al. 1998). The simulated rate of change in SOC during 50 years was 0.20 ± 0.03 $Mg\ ha^{-1}\ y^{-1}$ (181 ± 25 $lb\ ac^{-1}\ yr^{-1}$) at the Blackland Prairie site (table 3) and was not different between high and low fertilizer inputs within a tillage treatment.

At the Coastal Plain site, differences between measured and simulated SOC at 5 years ranged from −1.0% in NT (with manure) to 2.3% in CT (no manure). Simulated SOC values were within the standard error of measured values at 5 years (table 3 and figure 2h, 2k). Simulated SOC increased in all treatments, while measured SOC decreased the first year in all treatments. A decrease in measured SOC at 1 year was attributed to a drier than normal growing season, which resulted in a lower-than-average corn yield, and the fact that neither tillage nor manure system affected yield the first year of the study (Causarano et al. 2007). However, total measured rainfall during the corn crop growing season in the first year at the study site (mid-Apr through August) was 441 mm (17.4 in), and EPIC-generated total rainfall for the same period in the first year was 333 mm (13.1 in). The simulated average corn yield the first year was approximately one half (4.5 $Mg\ ha^{-1}$ [72 $bu\ ac^{-1}$]) of the 50-year average corn yield (8.4 $Mg\ ha^{-1}$ [134 $bu\ ac^{-1}$]). At 3 years, measured SOC increased in all treatments

Figure 1

EPIC-simulated soil organic C during 50 years of management in the Texas Blackland Prairie (0 to 20 cm depth), Alabama Coastal Plain (0 to 30 cm depth), and Mississippi Upland (0 to 15.2 cm depth) Major Land Resource Areas. Note that CT is conventional tillage, and NT is no tillage. Thick lines in each panel are non-linear regressions fit to simulation outputs.



except for CT without manure, and at the end of 5 years, both simulated and measured SOC increased. Measured 5-year average annual rainfall at the Coastal Plain study site was 1,215 mm (47.9 in) (Causarano et al. 2007), while EPIC-generated rainfall averaged 1,312 mm (51.7 in). Measured 5-year average annual temperature at the Coastal Plain site was 17.7°C (64°F), and EPIC-generated average annual temperature was 18.4°C (65°F). Total SOC sequestered during 50 years averaged 1.7 and 12.3 Mg ha^{-1} (0.8 and 5.5 tn ac^{-1}) without and with manure, respectively, under CT and 3.8 and 18.0 Mg ha^{-1} (1.7 and 8.0 tn ac^{-1}) without and with manure under NT (table 3). The simulated rate of change in SOC during 50 years was 0.18 ± 0.15 Mg ha^{-1} y^{-1} (159 ± 135 lb ac^{-1} yr^{-1}) at the Coastal Plain site. Dairy manure input had a large positive effect on simulated SOC at the end of 50 years at the Coastal Plain site, a result similar to that measured in the field at the end of 5 years (Terra et al. 2005). Other long-term field studies have also shown significant increases in SOC with animal manure input (Webster and Goulding 1989; Paustian et al. 1992; Buyanovsky and Wagner 1998).

Averaged across MLRAs and fertilizer conditions, the simulated annual rate of change in SOC during 50 years was greater under NT (0.19 Mg ha^{-1} y^{-1}) [170 lb ac^{-1} yr^{-1}]) than under CT (0.13 Mg ha^{-1} y^{-1} [116 lb ac^{-1} yr^{-1}]) ($p < 0.01$). Similarly, total SOC sequestered during 50 years of simulation was greater under NT (9.5 Mg ha^{-1} [4.2 tn ac^{-1}]) than under CT (6.3 Mg ha^{-1} [2.8 tn ac^{-1}]) ($p < 0.01$). Across the five MLRA and fertilizer conditions, sequestration of simulated SOC with NT compared with CT was 0.06 ± 0.03 Mg ha^{-1} y^{-1} [56 ± 26 lb ac^{-1} yr^{-1}]). These estimates of SOC sequestration with NT compared with CT were relatively low compared with compiled measured data from the southeastern United States, which were reported as 0.42 ± 0.46 Mg ha^{-1} y^{-1} (375 ± 411 lb ac^{-1} yr^{-1}) (Franzluebbers 2005). One of the reasons for the low estimate found in our simulation study may have been the longer period of evaluation (50 years) compared with most field studies (10 ± 5 years). The rate of simulated SOC accumulation was often much greater during the first few decades compared to the last decades, and therefore, computing a linear rate of change throughout the 50-year period reduced the estimate of SOC seques-

Figure 2

Simulated and measured soil organic C for the Texas Blackland Prairie with low fertilizer input (a, b, c), Texas Blackland Prairie with high fertilizer input (d, e, f), Alabama Coastal Plain without manure (g, h, i), Alabama Coastal Plain with manure (j, k, l), and Mississippi Upland (m, n, o) using different parameter sets optimized for each site (as indicated in column title). Error bars are from original data reported in Causarano et al. (2007) for the Alabama Coastal Plain site and Rhoton (2000) for the Mississippi Upland site.

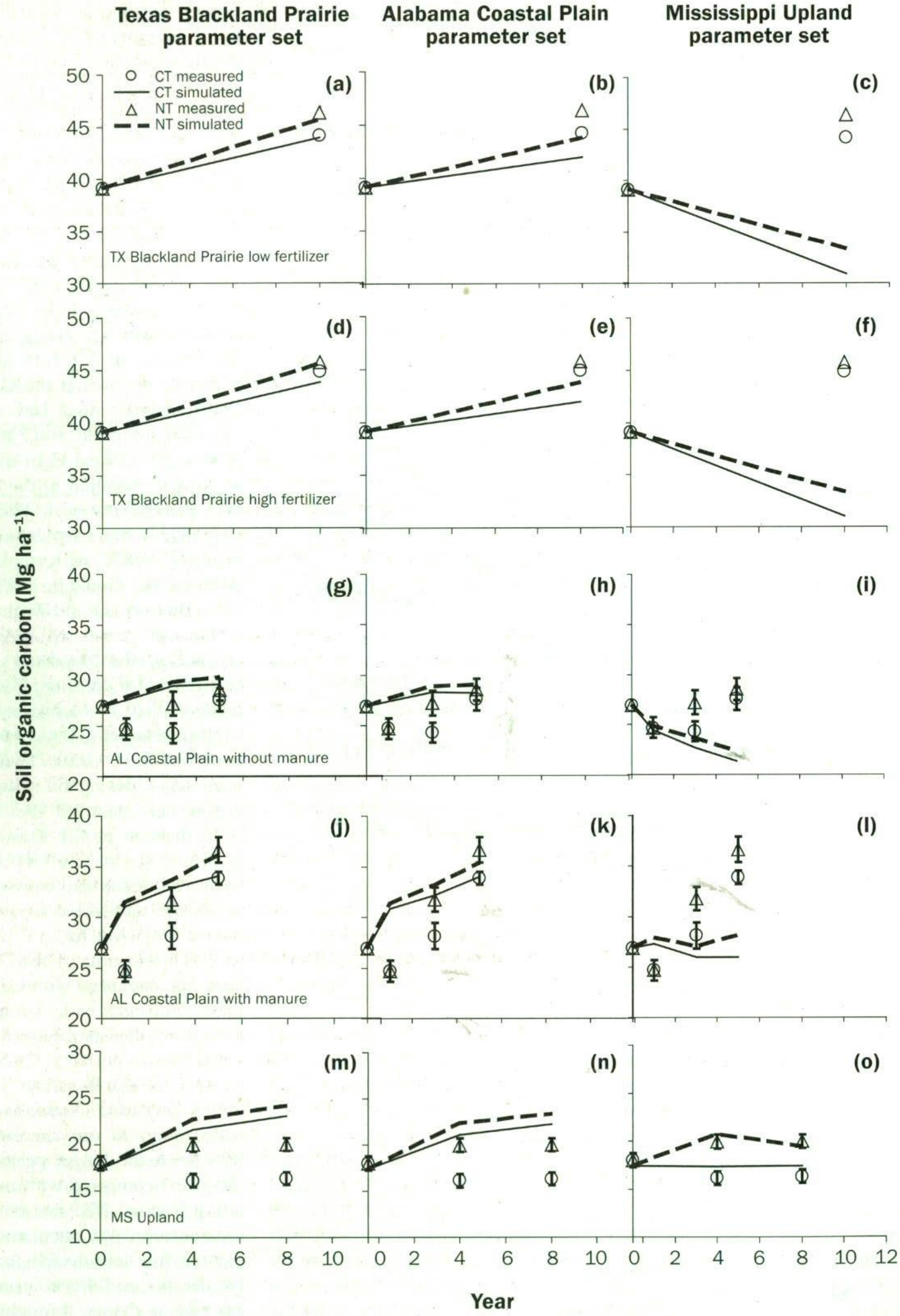
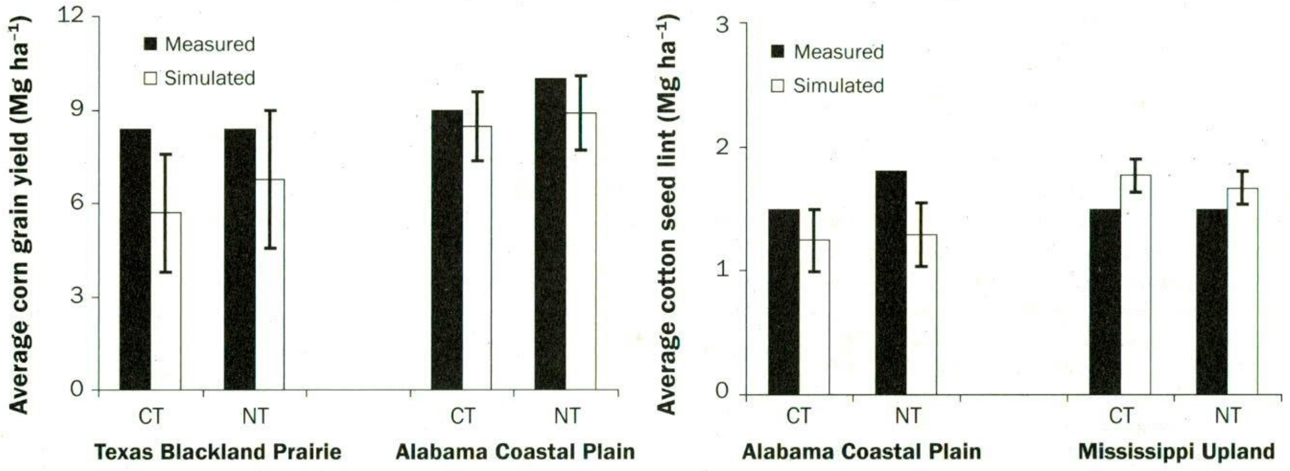


Figure 3

EPIC-simulated corn grain and cotton seed lint yields (means and standard deviations among years) during a 50-year simulation period. Measured yields were based on experimental conditions at the Blackland Prairie site (10 years) (Potter et al. 1998), the Coastal Plain site (5 years) (Causarano et al. 2007), and on the 50-year county-level reports from the USDA National Agricultural Statistics Service (2007) for the Mississippi Upland site. Note that CT is conventional tillage, and NT is no tillage.



tration compared with values during the first few years. Despite this difference in absolute change, EPIC v. 3060 was still able to effectively simulate relative differences in SOC sequestration between CT and NT.

Crop yields simulated by EPIC v. 3060 are shown in figure 3. At the Blackland Prairie site, simulated corn grain yield averaged 5.7 Mg ha^{-1} (91 bu ac^{-1}) under CT and 6.8 Mg ha^{-1} (108 bu ac^{-1}) under NT. Mean measured corn grain yield during 8 years was 8.4 Mg ha^{-1} (134 bu ac^{-1}) among all management systems. At the Coastal Plain site, corn grain yield averaged 8.7 Mg ha^{-1} (139 bu ac^{-1}), and cotton seed lint yield averaged 1.3 Mg ha^{-1} (0.6 tn ac^{-1}) during 50 years of simulation. Mean measured corn yield was 9.0 Mg ha^{-1} (143 bu ac^{-1}) for CT and 10.0 Mg ha^{-1} (159 bu ac^{-1}) for NT, and mean measured cotton seed yield was 1.5 Mg ha^{-1} (0.7 tn ac^{-1}) for CT and 1.8 Mg ha^{-1} (0.8 tn ac^{-1}) for NT during 5 years (Causarano et al. 2007). At the Mississippi Upland site, simulated cotton seed lint yield averaged 1.8 Mg ha^{-1} (0.8 tn ac^{-1}) across tillage systems. Measured cotton seed lint yields in Tate County Mississippi averaged 1.5 Mg ha^{-1} (0.7 tn ac^{-1}) from 1950 through 2000 (USDA NASS 2007).

Relationship of Environmental Policy Integrated Climate-Simulated Soil Organic Carbon with the Soil Conditioning Index. Environmental Policy Integrated Climate-simulated SOC at the end of 50 years of management was weakly related to SCI values (n = 10) (figure 4a). The SCI values were positive for all NT systems and negative for all CT systems. When combining the data in this study with data derived from uncalibrated EPIC v. 3060 simulations from a Blackland Prairie site, a South Carolina Coastal Plain site, and a Georgia Southern Piedmont site (Abrahamson et al. 2007), differences between the two data sets were not obvious. However, simulated SOC for the Blackland Prairie site under CT and for the Alabama Coastal Plain site under CT with dairy manure addition were greater than with the original relationship reported in Abrahamson et al. (2007). The strength of the relationship between EPIC-simulated SOC and SCI across all data simulated in the southeastern United States from the previous and current simulation studies (n = 19) suggests that either EPIC v. 3060 or SCI could be useful tools to predict SOC changes under CT and NT management in the southeastern United States. However, more measured data from the southeastern United States are needed to validate the relationship and to develop better estimates of SOC sequestration amounts and rates with the SCI.

The range of SCI values was greater between tillage systems than between C sources, such as crop biomass and organic fertilizer. This suggests that the SCI was more sensitive to tillage practices than to C inputs from manure or crop biomass. Hubbs et al. (2002) found that cover crops, double cropping systems, and level ground, which contributed to low erosion rates, resulted in positive SCI values across several studies in the southeastern United States. The SCI results were qualitatively consistent with predictions of SOC using EPIC v. 3060 in our study.

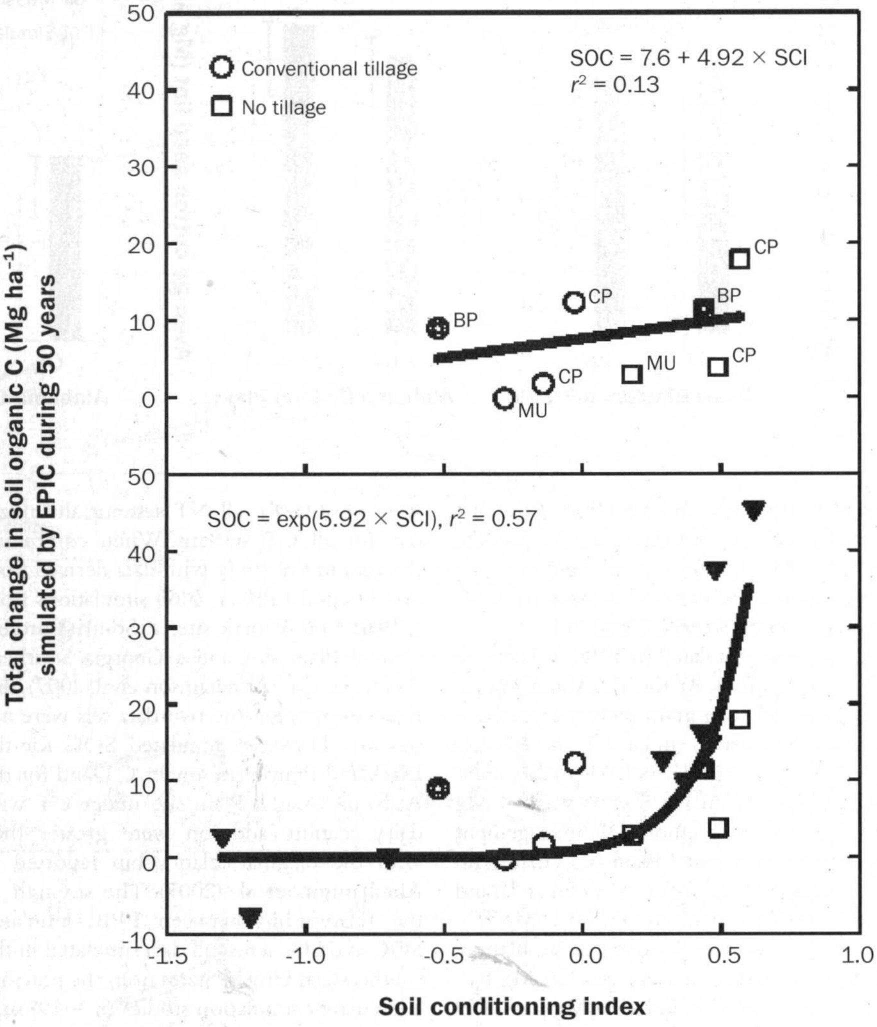
Parameter Set Comparisons. Simulating the change in SOC during 50 years using a single parameter set for all of the MLRAs resulted in two favorable outcomes (figure 5). Use of the parameter set optimized for the Blackland Prairie site resulted in qualitatively similar SOC predictions among tillage systems and fertilizer conditions for the Coastal Plain site (figure 5b) and Mississippi Upland site (figure 5c). Prediction of SOC change for the Coastal Plain site using the Blackland Prairie parameter set was within the 95% confidence interval of that predicted using the optimized parameter set for the Coastal Plain site in both CT and NT with dairy manure fertilizer but was overpredicted in both tillage systems without dairy manure fertilizer. Change in SOC was overpredicted at the Mississippi Upland site under both CT and NT.

Use of the parameter set optimized for the Coastal Plain site resulted in qualitatively similar SOC predictions among tillage systems and fertilizer conditions for the Blackland Prairie site (figure 5a) and the Mississippi Upland site (figure 5c). Prediction of SOC change for the Blackland Prairie site using the Coastal Plain parameter set was within the 95% confidence interval of that predicted with the optimized parameter set for the Blackland Prairie site under NT only but was underpredicted under CT. Change in SOC was overpredicted at the Mississippi Upland site under both CT and NT.

Use of the parameter set optimized for the Mississippi Upland site resulted in poor agreement in SOC predictions at the Blackland Prairie site (figure 5a) and the Coastal Plain site (figure 5b). Unique conditions appear to be present at the Mississippi Upland site that prevent the broad utilization of EPIC v. 3060 parameters across all of the locations used in this study. Further research and additional measures of SOC are needed to determine how the EPIC model could be improved to address these differences.

Figure 4

Relationship of EPIC-simulated soil organic C accumulation during a 50-year period with the soil conditioning index among the 10 observations in the current study (top panel) and including additional data from Abrahamson et al. (2007) (bottom panel). Additional data in bottom panel included conventional and no tillage management of cotton cropping systems in the Blackland Prairie of Texas, Coastal Plain of South Carolina, and Southern Piedmont of Georgia. Note that BP is Blackland Prairie, CP is Coastal Plain, and MU is Mississippi Upland.



Summary and Conclusions

A limited number of sensitive parameters were optimized in EPIC v. 3060 for successful validation of surface soil organic carbon (SOC) against three 5- to 10-year long field experiments in Texas, Alabama, and Mississippi. Sequestration of SOC using the optimized parameter sets during 50 years of simulation across locations was greater under no tillage (9.5 ± 6.2 Mg ha^{-1} [4.2 + 2.8 tn ac^{-1}]) (mean + standard deviation among the five site-fertilizer conditions) than under conventional tillage (6.3 ± 5.3 Mg ha^{-1} [2.8 + 2.4 tn ac^{-1} yr^{-1}]). Although simulated SOC using EPIC v. 3060 was only weakly related to predictions under the same conditions using the soil conditioning index (SCI), there was a positive trend between the two model simulations. However, when simulated data in this study were combined with simulated data from other locations in the southeastern United States, there was a strong nonlinear relationship between SOC simulated with EPIC v. 3060 and the SCI. Transferability of optimized parameter sets across locations was possible under certain conditions but not all, indicating the need for further mechanistic understanding and testing under more diverse conditions. This study shows that EPIC v. 3060 and the SCI could be useful, relatively inexpensive, expedient tools to determine SOC storage among different tillage and residue management systems in the southeastern United States. Routine use of the SCI in Natural Resources Conservation Service field offices with calibrated SOC estimates could help promote soil conservation and C offset trading. However, further research is needed to determine the applicability of the approaches to a wider range of management situations in the southeastern United States, as well as to define the key variables and processes in models affecting SOC across soils, management, and climatic conditions.

Acknowledgements

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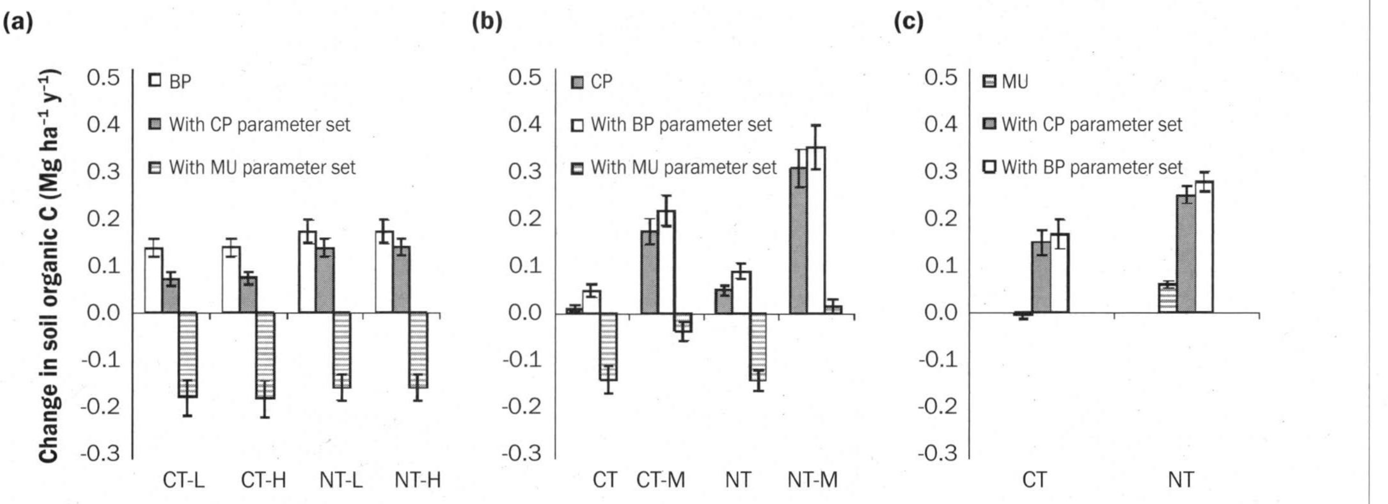
Figure 5

EPIC-simulated change in soil organic C during 50 years using optimized parameter sets within and across sites: (a) Texas Blackland Prairie (BP); (b) Alabama Coastal Plain (CP); (c) Mississippi Uplands (MU). Error bars are 95% confidence intervals derived from deviations from a linear regression of 50-year data observations. Note that CT is conventional tillage, NT is no tillage, L is low fertilizer, H is high fertilizer, and M is with manure addition.



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Improving construction site runoff quality with fiber check dams and polyacrylamide

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Abstract: Sediment and turbidity are among the most common pollutants affecting surface waters, resulting in reduced reservoir capacity, degradation of aquatic organism habitat, and decreased aesthetic value. Construction activities, including roadway projects, can be significant contributors to sediment loading in streams and lakes. We studied water quality in stormwater runoff from three systems for erosion and sediment control on two roadway projects in the North Carolina mountains. The first roadway project was divided into three experimental sections, each with one the following treatments installed in the adjacent drainage ditch: (1) the standard best management practice (BMP) consisting of narrow sediment traps in the ditch along with rock check dams, (2) fiber check dams (FCDs) consisting of a mix of straw wattles and coir logs, or (3) FCDs with granulated, anionic polyacrylamide (PAM) added to each. The second project was smaller and included only two of the experimental sections described above: (1) the standard BMPs and (2) FCDs with PAM. Significant reductions in turbidity and total suspended solids were obtained using the FCDs, particularly those with PAM added. At site 1, from June 2006 to March 2007, the average turbidity values for the stormwater runoff were 3,813 nephelometric turbidity units (NTU) for the standard BMPs, 202 NTU for the FCDs-only, and 34 NTU for the FCDs with PAM. Average turbidity in discharges at site 2 was reduced from 867 NTU for the standard BMPs to 115 NTU for the FCDs with PAM. Sediment loading at both sites was similarly reduced with the use of FCDs. At site 1, the standard BMPs lost an average of 428 kg (944 lb) of sediment per storm event compared to just 2.1 kg (4.6 lb) for the FCDs-only and 0.9 kg (2.0 lb) for the FCDs with PAM. At site 2, the standard BMPs lost an average of 3.3 kg (7.3 lb) per storm event compared with 0.8 kg (1.8 lb) for the FCDs with PAM. A conservative economic analysis suggests that the costs of the FCDs are lower than the standard BMPs. This study suggests that the use of FCDs with PAM can bring discharges from similar linear construction projects much closer to the regulatory guidelines for non-point source discharges than the current standard practices.

Key words: check dams—erosion control—polyacrylamide (PAM)—sediment loading—turbidity reduction—wattles

A recent assessment of the conditions of the rivers and streams in the United States indicated that 45% of the total length assessed was classified as impaired for their intended use, with sediment and siltation as the leading cause (US Environmental Protection Agency 2002). Construction activity, including roadway projects, can be a significant contributor to sediment loading, with erosion rates up to 100 times that of cropland (Pitt et al. 2007; Wolman 1967). Concentrations of suspended sediment have been reported for construction site discharges well over 1,000 mg L^{-1} (1,000 ppm) and as high as 160,000 mg L^{-1} (Markusic 2007; Wolman and Schick 1967; Line and White 2001). The effects of suspended solids on aquatic organisms have been shown to be dependent on exposure time and concentration, but even low concentrations for a matter of hours can

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